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## **The Probability of Laser Caused Ocular Injury to the Aircrew of Undetected Aircraft Violating the Exclusion Zone about the Airborne AURA LIDAR**

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# The Probability of Laser Caused Ocular Injury to the Aircrew of Undetected Aircraft Violating the Exclusion Zone about the Airborne AURA LIDAR

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## **Abstract**

The probability of a laser caused ocular injury, to the aircrew of an undetected aircraft entering the exclusion zone about the AURA LIDAR airborne platform with the possible violation of the Laser Hazard Zone boundary, was investigated and quantified for risk analysis and management.

## **Summary**

The probability of an actual ocular injury occurring as a result of undetected aircraft violating the **Exclusion Zone** of the airborne AURA is on the order of **one in four hundred million** and the probability for an actual ocular injury occurring as a result of an undetected aircraft violating the **Laser Hazard Zone** of the airborne AURA is on the order of **one in 9 million**.

## **Acknowledgement**

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## **I. Introduction**

The laser hazard presented by the airborne AURA LIDAR/Sandia Remote Sensing System was described in previously released SAND reports<sup>1,2</sup>. The laser hazard analysis was based on current laser safety standards<sup>3,4</sup>. The “exclusion zone”, about the AURA airborne platform, described in those reports is an **administrative control**, which is intended to prevent the accidental exposure and possible ocular injury to aircrew members of other nearby aircraft by terminating laser transmission upon the approach and breach of the boundary of this zone by the other aircraft. An aircraft entering the “exclusion zone”, undetected, does not in and of itself ensure that an ocular injury will occur as a result of a possible exposure to the activated AURA laser system.

### **Exclusion Zone**

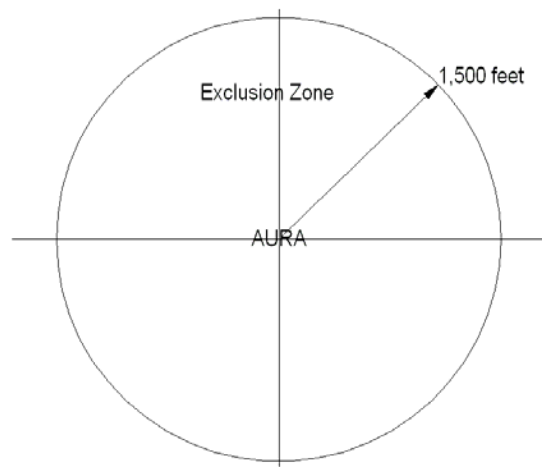


Figure 1

A spherical exclusion zone with a 1500 foot radius is administratively maintained about the AURA airborne platform.

The administratively established exclusion zone (**EZ**), is depicted as a spherical space about and centered on the airborne AURA platform with a 1500 foot radius. This radius is based upon the single pulse Nominal Ocular Hazard Distance (**NOHD**), of 1480 feet (rounded up to 1500 feet), appropriate for the maximum output of the AURA laser at its most hazardous wavelength (1064 nm). The Laser Hazard Zone (**LHZ**) is inclusive to the exclusion zone of the airborne AURA. The potential for an ocular exposure to the AURA laser exists only within the LHZ of the EZ.

## Laser Hazard Zone

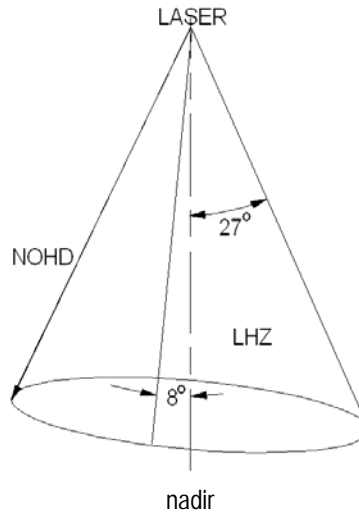


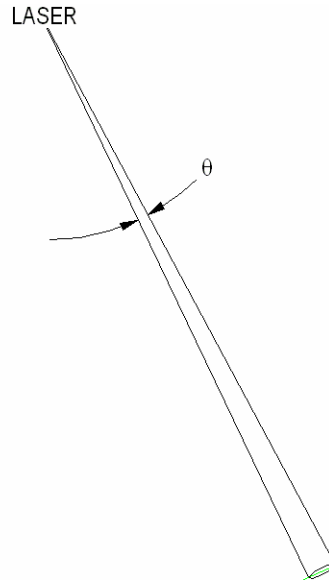
Figure 2

The laser hazard zone (LHZ) is an elliptical cone described by the angular extents of the gimbal system extending out to a range defined by the Nominal Ocular Hazard Distance (NOHD) for the maximum single pulse output of the AURA laser's most hazardous wavelength.

The laser hazard zone (**LHZ**) is that airspace about the AURA airborne platform where the laser beam can produce a radiant output above the Maximum Permissible Exposure (**MPE**) level. Not all the **exclusion zone** airspace about the AURA airborne platform contains the laser hazard zone. The laser hazard zone is that airspace described by a solid elliptical cone. The volume of this cone bounded by the maximum extends of the gimbal system and extending radially out to the single pulse IR output NOHD (1480 feet). The maximum extends of the gimbal is  $\pm 27$  degrees about the Pitch axis and  $\pm 8$  degree about the Roll axis. The laser beam may be propagated anywhere within this space fixed on a stationary ground target. Undetected aircraft entry into this "hazard zone" does not in and of itself ensure that an ocular exposure, with an accompanying ocular injury to the aircrew, will occur; but rather that there exists a possibility that an ocular injury can occur. The goal of this report is to calculate the probability that an undetected aircraft entry into the hazard zone and the probability that ocular injury could occur.



## **Laser Beam Geometry**



**Figure 3**

The laser beam is propagated in a cone-like geometry expanding by the beam divergence ( $\theta$ ).

The AURA laser beam occupies a physical space describe by an approximation of a solid cone, expanding from the exit port of the airborne platform. The apex of the cone is approximated by the beam divergence. The intrabeam exposure to the laser beam within this space can cause ocular injury out to the NOHD.

## **Conditions for Ocular Injury**

The conditions that must be met for an ocular injury to occur from an exposure to this laser are that (1) the eye of the individual must be intrabeam (inside the actual beam path and aligned to or looking at the laser exit), (2) within the extent of the LHZ at the time of laser emission, and be inside the NOHD, (3) such that the exposure to the laser is above the MPE. For typical relative airspeeds between the AURA airborne platform and another aircraft, the number of laser pulses that would occur with these conditions met is at most one and only one laser pulse.

## **II. Probability of Ocular Injury**

The probability of ocular injury involves a spatial probability component (intrabeam within the hazard zone) and a temporal probability component (intrabeam at the time of laser emission).

$$P(injury) = P(spatial) \cdot P(temporal)$$

### **Spatial Probability**

The exiting AURA laser beam projects a cross-sectional area ( $S_{beam}$ ) onto the spherical surface of a hemisphere of radius “R”, beneath the airborne platform, out to a maximum “hazard” radius defined by the NOHD. The projected area is circular and scaled by the radial distance from the exit. The LHZ is bounded by the extends of the telescope gimbal system and projects an elliptical area ( $S_{LHZ}$ ) on to the surface of this hemisphere of radius “R” beneath the airborne platform, out the maximum “hazard” radius defined by the NOHD.

The worst case probability that the actual laser beam path will intersect the observer’s eye within the hazard zone can be determined by the comparison of the two projected areas. This assumes that the observer’s eye will always be “aligned” (intrabeam) to the laser exit port.

The projected area onto the spherical surface of radius “R” is defined\* as:

$$S = \Omega \cdot R^2$$

#### **Where**

$S$	Surface area on the spherical surface
$\Omega$	Solid angle of the apex of the projection
$R$	Radius of the sphere (hemisphere)

\*wikipedia.org defines the solid angle as:  $\Omega = \frac{S}{R^2}$

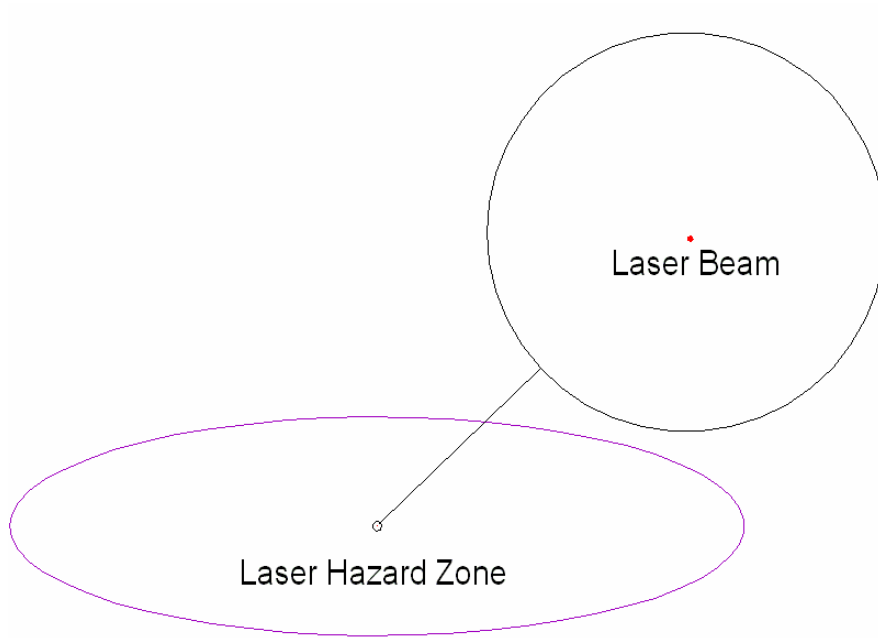


Figure 4

The shape of the laser beam cross-sectional area inside the area of the LHZ projected onto the surface of a sphere at a radial distance from the exit of the AURA gimbal system is an approximate small circle inside of an ellipse. The spatial probability of ocular exposure inside the LHZ can be found by the comparison of these two areas.

The spatial probability can be determined by the comparison of the two areas projected on the surface of a sphere at a radial distance “R” out to a maximum radius defined as the NOHD, while assuming the temporal probability is set to: “1.0” (CW laser operation).

$$\begin{aligned}
 P(spatial) &= \frac{S_{beam}}{S_{LHZ}} \\
 &= \frac{\Omega_{beam} \cdot R^2}{\Omega_{LHZ} \cdot R^2} \\
 P(spatial) &= \frac{\Omega_{beam}}{\Omega_{LHZ}}
 \end{aligned}$$

The spatial probability, based the on comparison of solid angles is independent of the radial distance from the exit port of the AURA airborne platform.

The **solid angle** for the laser beam ( $\Omega_{beam}$ ), approximated by a solid cone, with the apex angle of the cone set equaled to the beam divergence ( $a = \theta$ ), is given by [wikipedia.org](http://wikipedia.org) as:

$$\Omega_{beam} = 2\pi \left( 1 - \cos \frac{\theta}{2} \right) \text{ steradians}$$

Alternately for angles less than 5 degrees the small angle approximation can be applied which yields a simplified form:

$$\Omega_{beam} = \frac{\pi \cdot \theta^2}{4} \text{ sr} \quad [ANSI Std. Z136.1-2000 (Eq. B91)]$$

For a beam divergence of 500 micro-radians:

$$\begin{aligned} \Omega_{beam} &= 2\pi \left( 1 - \cos \frac{\left\{ 500 \times 10^{-6} \text{ rad} \cdot \frac{180^\circ}{\pi \text{ rad}} \right\}}{2} \right) \text{ sr} \quad \text{or} \quad \Omega_{beam} = \frac{\pi \cdot (500 \times 10^{-6})^2}{4} \text{ sr} \\ &= 2\pi \left( 1 - \cos \frac{\left\{ 28.65 \times 10^{-3} \right\}^\circ}{2} \right) \text{ sr} \quad \text{or} \quad = \frac{\pi \cdot (250 \times 10^{-9})}{4} \text{ sr} \\ &= 2\pi \left( 1 - \cos \left\{ 14.32 \times 10^{-3} \right\}^\circ \right) \text{ sr} \quad \text{or} \quad = \frac{785 \times 10^{-9}}{4} \text{ sr} \end{aligned}$$

$$\Omega_{beam} = 196 \times 10^{-9} \text{ sr}$$

The solid angle for the LHZ ( $\Omega_{LHZ}$ ) approximated by an elliptical cone with a major apex angle ( $a_{major}$ ) of 54 degrees and a minor apex angle ( $a_{minor}$ ) of 16 degrees. The effective apex angle of an elliptical cone is the average of the two.

$$\begin{aligned}
a_{effective} &= \frac{a_{major} + a_{minor}}{2} \\
&= \frac{54^\circ + 16^\circ}{2} \\
a_{effective} &= 35^\circ \quad (\text{Small angle approximation does not apply})
\end{aligned}$$

The solid angle for the LHZ ( $\Omega_{LHZ}$ ) is:

$$\begin{aligned}
\Omega_{LHZ} &= 2\pi \left( 1 - \cos \frac{35^\circ}{2} \right) sr \\
&= 2\pi (1 - \cos 17.5^\circ) sr \\
\Omega_{LHZ} &= 291 \times 10^{-3} sr
\end{aligned}$$

Hence, the spatial probability can be expressed as:

$$\begin{aligned}
P(spatical) &= \frac{\Omega_{beam}}{\Omega_{LHZ}} \\
&= \frac{196 \times 10^{-9} sr}{291 \times 10^{-3} sr} \\
P(spatical) &= 675 \times 10^{-9} \text{ or } 1:1.48 \times 10^6
\end{aligned}$$

There is about a one in a million and a half chance that an aircrew member's eye will intersect the laser beam inside the defined LHZ (assuming that the eye is always aligned with the laser output – looking up the beam path to the laser exit port, while the laser is “on”).

## **Temporal Probability**

The temporal probability pertains to likeliness of an ocular exposure above the MPE will occur while the “aligned eye” is in the beam path (the spatial probability is set to: “1.0”).

### **CW Exposure**

The temporal probability of an ocular injury occurring (while the “aligned eye” is traveling through the cross section of the “beam path” exposed to a CW laser) is, by definition: “1.0” and the overall probability of ocular injury is than just the spatial probability.

### **Pulse Exposure**

The probability of an ocular injury occurring while the “aligned eye” is traveling through the cross-section of the beam path while exposed to a multiple pulsed laser is the ratio of the time the “aligned eye” is in the beam path to the time between laser pulses – for the condition where the aligned eye is subjected to only one (possible) laser pulse.

$$P(\text{temporal}) = \frac{\text{Time in beam path}}{\text{Time between pulses}}$$

### **Duty Cycle**

The duty cycle of the AURA laser is the ratio of the laser “on” time to the time between laser pulses.

$$\text{duty cycle} = \frac{t}{T}$$

Where;

- |     |   |
|-----|---|
| $t$ | Is the laser pulse width                              |
| $T$ | Is the period of the pulse repetition frequency (PRF) |

The period ( $T$ ) is the inverse of the PRF.

$$T = \frac{1}{PRF}$$

$$duty\ cycle = \frac{t}{\frac{1}{PRF}}$$

$$duty\ cycle = t \cdot PRF$$

$$duty\ cycle = (10 \times 10^{-9} \text{ sec}) \cdot (30 \text{ sec}^{-1})$$

$$duty\ cycle = 300 \times 10^{-9}$$

The duty cycle for the AURA laser is small; however, if the “aligned eye” is looking at the laser exit while inside the laser beam path at the time of laser emission an ocular injury will likely occur if the radiant exposure is above the MPE.

The probability of an actual ocular injury occurring (as a consequence of an undetected aircraft breaching the LHZ, with an eye looking along the beam path at the instant of laser emission, where the radiant exposure at the eye is above the MPE) is dependent upon the aligned eye’s transit time through the cross-section of the actual beam path to the time between laser pulses. This comparison gives rise to the temporal probability component.

The laser spot size is a function of the distance from the laser and the beam divergence.

$$d_R = d_o + \theta R$$

Where

- $d_R$  Is the laser beam spot diameter at a distance R from the laser
- $d_o$  The diameter of the laser beam at exit
- $\theta$  Beam divergence
- $R$  The distance from the laser

The relative airspeed between the AURA airborne platform and another aircraft is dependent upon the respective velocity vectors of the aircraft involved. The likelihood of an aircraft breaching the EZ and the LHZ undetected is greater for an aircraft approaching from directions ranging from the front of the AURA to the sides of the

AURA rather than for an aircraft approaching from directions ranging from the rear to the sides of the AURA airborne platform.

The closing velocity is the vector sum of the AURA velocity vector and the undetected aircraft velocity vector.

$$\vec{V}_{closing} = \vec{V}_{AURA} + \vec{V}_{undetected\_aircraft}$$

The “eye” transit time through the LHZ can be calculated as:

$$T_{eye} = \frac{d_R}{\vec{V}_{closing}}$$

Since the velocity vector of the undetected aircraft is unknown at this time the worst case for the “undetected” condition (described above) the velocity vectors of the two aircrafts intersect at 90 degrees (side to side approach). The closing velocity vector will be greater than the AURA’s relative airspeed of the 90 knots (46.3 m/sec)<sup>1</sup>.

Choosing the AURA velocity will give rise to a conservative bias to the analysis.

The vertical separation between the AURA and the undetected aircraft is also not known at this time. The largest spot size for the worst case occurs at the boundary of the LHZ at the NOHD (451 m)<sup>1</sup>.

$$d_r = d_{r_{max}} = d_{NOHD}$$

$$\begin{aligned} d_{NOHD} &= 10^{-2} m + (500 \times 10^{-6}) \cdot (451 m) \\ &= 10 \times 10^{-3} m + 226 \times 10^{-3} m \end{aligned}$$

$$d_{NOHD} = 236 \text{ mm}$$

$$d_{NOHD} = 23.6 \text{ cm}$$

The longest transit time for the “eye” is:

$$T_{eye} = \frac{236 \times 10^{-3} m}{46.3 \text{ m/sec}}$$

$$T_{eye} = 5.10 \times 10^{-3} \text{ sec} = 5.1 \text{ ms}$$



The time between laser pulses is:

$$T_{PRF} = \frac{1}{30 \text{ sec}^{-1}} = \left( \frac{1}{30} \right) \text{sec}$$

The temporal probability of an ocular exposure is the ratio of the transit time of the eye through the LHZ to the time between laser pulses:

$$\begin{aligned} P(\text{temporal}) &= \frac{T_{eye}}{T_{PRF}} \\ &= \frac{5.1 \times 10^{-3} \text{ sec}}{\left( \frac{1}{30} \right) \text{sec}} \\ &= (5.1 \times 10^{-3}) \cdot (30) \\ P(\text{temporal}) &= 153 \times 10^{-3} \text{ or } 1:6.54 \end{aligned}$$

The probability that the aligned “eye” will still be in the LHZ during laser emission is one out of six and a half.

The probability of an actual ocular injury occurring as a consequence of an undetected aircraft breaching the LHZ, with an eye aligned to the laser (intrabeam) in the beam path at the instant of laser emission with a radiant exposure at the eye above the ocular MPE is:

$$\begin{aligned} P(\text{injury}) &= P(\text{spatial}) \cdot P(\text{temporal}) \\ &= (675 \times 10^{-9}) \cdot (153 \times 10^{-3}) \\ P(\text{injury}) &= 103 \times 10^{-9} \text{ or } (1:9.68 \times 10^6) \end{aligned}$$

The worst case probability of an actual ocular injury, due to an undetected aircraft entry in the **Laser Hazard Zone** is on the order of **one in** more than **nine and a half million**.

## Exclusion Zone

Similarly the probability of ocular injury, due to an undetected aircraft entry into the spherical “**exclusion zone**” (*EZ*) can be determined from the ratio of the solid angles (the solid angle for the entire *EZ* sphere is  $4\pi$  steradians).

$$\begin{aligned}
 P(\text{spatial}) &= \frac{\Omega_{\text{beam}}}{\Omega_{EZ}} \\
 &= \frac{2\pi \cdot \left(1 - \cos \left\{ 14.32 \times 10^{-3} \right\}^\circ\right) sr}{2\pi \cdot \left(1 - \cos \frac{360^\circ}{2}\right) sr} \\
 &= \frac{1 - \cos \left\{ 14.32 \times 10^{-3} \right\}^\circ}{1 - \cos 180^\circ} \\
 &= \frac{31.2 \times 10^{-9}}{1 - (-1)} \\
 &= \frac{31.2 \times 10^{-9}}{2}
 \end{aligned}$$

$$P(\text{spatial}) = 15.6 \times 10^{-9} \text{ or } 1:64.1 \times 10^6$$

There is a one in about a **sixty-four million** plus chance that an aircrew member’s eye will intersect the laser beam inside the *EZ* about the AURA aircraft.

The worst case probability of an actual ocular injury occurring as a consequence of an undetected aircraft breaching the *EZ* is:

$$\begin{aligned}
 P(\text{injury}) &= P(\text{spatial}) \cdot P(\text{temporal}) \\
 &= (15.6 \times 10^{-9}) \cdot (153 \times 10^{-3}) \\
 P(\text{injury}) &= 2.39 \times 10^{-9} \text{ or } (1:419 \times 10^6)
 \end{aligned}$$

The probability of an actual ocular injury, due to an undetected aircraft entry in the **Exclusion Zone** is on the order of **one in** about **four hundred million**.

### **III. Conclusion**

The worst case probability of an ocular injury occurring as a result of an undetected aircraft entering the **Exclusion Zone** about the AURA airborne platform during laser operation is on the order of one in **four hundred million**.

The worst case probability of an ocular injury occurring as a result of an undetected aircraft entering the **Laser Hazard Zone** of the of the exclusion zone about the AURA airborne platform during laser operation is on the order of one in **nine million**.

This does not preclude the necessity for diligence on the part of the “spotters” in alerting the laser operator to the fact that another aircraft may enter the AURA “exclusion zone”.

Although the probability of ocular injury is relatively low it does exist. In fact, if the “aligned” eye is intrabeam at the time of laser emission within the NOHD the probability of ocular injury is 100%.

#### **IV. References**

1. SAND2004-0413, Laser Hazard Analysis for the Airborne AURA (Big Sky Variant) Proteus Platform, Arnold L Augustoni, February 2004.
2. SAND2004-4110, Extended Ocular Hazard Distances Associated with Intrabeam Aided Viewing of the Sandia Remote Sensing System Airborne AURA Laser (Big Sky Variant), Arnold L. Augustoni, August 2004.
3. ANSI Standard Z136.1-2000, for Safe Use of Lasers, Published by the Laser Institute of America.
4. ANSI Standard Z136.6-2005, for Safe Use of Lasers Outdoors, Published by the Laser Institute of America.

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